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## A Sample of Field Ellipticals

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### ABSTRACT

Using well-defined selection criteria applied to the LEDA galaxy catalogue we have constructed a sample of elliptical galaxies that can be taken to lie in the field. Such criteria can easily be applied to theoretical simulations for direct comparison with observations. The variation of the number of ‘isolated’ ellipticals with selection criteria is also investigated. A preliminary study of the environment of the field ellipticals shows that, in the mean, they are surrounded by a population of dwarf galaxies, out to projected radii of at least 500 kpc, with a radial density profile of  $r^{-0.6 \pm 0.2}$  and a luminosity function slope of  $\alpha \sim -1.8$ . The results are compared and contrasted to the satellite population around isolated spiral galaxies.

*Subject headings:* galaxies: elliptical and lenticular — galaxies: clusters: general — surveys

## 1. Introduction

From the many observations of the two-point correlation function, both in its angular (e.g. Lidman and Peterson 1996, Maddox et al. 1990) and spatial (e.g. Ratcliffe et al. 1998, Giuricin et al. 2001) form, it is now well established that galaxies are clustered out to distances of at least 10 Mpc. In addition, numerous studies of the distribution of bright galaxies (e.g. Dressler 1980) show that elliptical galaxies preferentially occur in regions of high galactic density whilst spiral galaxies dominate in the field. These basic observations have led to a multitude of theoretical simulations to explain the observed clustering properties and morphological segregation (e.g. Baugh et al. 1996). A major implication of the majority of these models is that elliptical galaxies are formed from the merger of many sub-clumps during the early stages of the evolution of the Universe. Although not ruling out the presence of elliptical galaxies in low density environments, the hierarchical models suggest that on average they are very different from the cluster ellipticals, with likely evidence of recent star-formation and/or merger events. There have been many studies of elliptical galaxies in low-density environments with somewhat inconclusive results, with some studies suggesting only minor star formation at low redshifts (e.g. Silva and Bothun 1998, Bernardi et al. 1998) whilst other studies have shown strong evidence for recent merger/star formation activity (e.g. Treu et al., 1999, 2001, Kuntschner et al. 2002).

A major problem with the current comparisons between theory and observation is the lack of a consistent definition of a field galaxy. Several of the studies (e.g. Treu et al. 1999, 2001, 2002, Aars et al. 2001) use redshift surveys of the brighter galaxies to derive a sample of isolated ellipticals. However, the incompleteness of the redshift catalogues may lead to the inclusion of several ellipticals that have close neighbours. This has led many to a final visual inspection to confirm their isolated nature, destroying the objectiveness of the selection criteria. Only using an extensive redshift survey can an objective sample be constructed (e.g. Kuntschner et al. 2002) but even then incompleteness in the catalogue can lead to erroneous selection of non-field galaxies. The studies have also concentrated on the properties of the galaxies themselves, with little, if any, analysis of the local environment of the elliptical which, from the morphology-density relationship, is likely to also have a very significant effect on the properties of the elliptical galaxy.

In this paper, we use an objective definition of a field galaxy applied to an all-sky galaxy catalogue that can also be applied to the theoretical simulations. We also investigate the variation of the number of field ellipticals with selection criteria. Using all-sky photographic surveys we have made a preliminary study of the environment of these galaxies in a search for a surrounding faint dwarf galaxy population.

## 2. Determination of the Field

The presence of satellite galaxies around much brighter galaxies and the possible presence of large numbers of dwarf galaxies in the field greatly complicates the selection of a field sample. At present, our knowledge of the faint end of the galaxy luminosity function (LF) is very uncertain. Studies of clusters have produced widely varying results, although evidence is increasing of a relationship between the local galaxy density and the gradient of the function at the faint end (e.g. Driver et al. 1998). The investigations suggest that in low density regions on the outskirts of clusters there should be a large population of dwarf galaxies. This may imply that in the field a large dwarf population also exists. Results from the recent major redshift surveys (e.g. 2dF, Norberg et al. 2002) suggest that the field LF is relatively flat. However, incompleteness and a selection bias against low surface brightness galaxies may lead to a flatter slope. Using the sample of galaxies selected by Zaritsky et al. (1993, 1997; hereafter ZSFW) Morgan et al. (1998) found evidence that, on average, the faint end slope of the LF in the fields of isolated spirals is steep, with  $\alpha \sim -1.8$ . Although this is consistent with that found in the outer regions of clusters, there is a major discrepancy between this result and our knowledge of the LF in the field and the Local Group, the latter having a flat faint-end of the LF (Mateo 1998). Roberts et al. (2003) have also found evidence that the slope of the field LF is flat. With the uncertainty in the field LF beyond  $M_B \sim -17$  (for  $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$  as adopted throughout) and the general consistency of the LF shape at the bright end (e.g. Driver and de Propris 2003), we concentrate here on defining a field galaxy as that which does not have nearby bright ( $M_B \sim -17$ ) neighbours such that it has not been seriously disturbed by its current local environment.

ZSFW, in their study of isolated spiral galaxies, used two criteria to select their sample. To be isolated, the magnitude difference between a neighbour and the ‘parent’ must be greater than 0.7 mag for galaxies within a projected distance of 1 Mpc or greater than 2.2 mag within 500 kpc. With an average separation of galaxies of about 1.5 Mpc (e.g. Nolthenius and White 1987), then the first of these criteria should ensure that the haloes do not interfere whilst the second is the true isolation criteria, ensuring that the galaxy does not lie in a cluster or a rich group. The application of these criteria is shown as a schematic in Fig. 1. Using these criteria the Magellanic Clouds would count as satellites but the Local Group would fail the criteria due to the close spacing of M31 and the Milky Way. Even the rather isolated elliptical galaxy NGC 720 (Dressler et al. 1986) would not be considered a field galaxy under our demanding criterion. ZSFW results, with a lack of any neighbouring satellites beyond a galactocentric distance of about 500 kpc, lent strong support to this classification of isolated galaxies.

### 3. The Sample

The availability of catalogues of large numbers of galaxies now makes it possible to investigate the dependency of galaxy morphology on environmental properties. Primary sources of information on galaxies are the Lyon Extragalactic Database (LEDa) and the NASA/IPAC Extragalactic Database (NED). In this study we use the LEDa catalogue. This database, constructed from a collection of sub-catalogues and other sources, currently contains data for over one million galaxies. More recent catalogues, such as that from the APM and the SDSS, concentrate primarily on the fainter galaxies and therefore are not complete at the bright end and cannot be reliably used for the selection of bright, isolated, galaxies over the whole sky. Using the LEDa catalogue we have derived samples of elliptical galaxies satisfying several criteria. Firstly, the redshift of the primary galaxy must be less than  $10,000 \text{ km s}^{-1}$  to ensure that the sample is approximately complete. To ensure that a reasonably accurate value for the distance could be derived assuming a uniform Hubble flow, an inner redshift limit of  $1500 \text{ km s}^{-1}$  was also applied. Secondly, the absolute magnitude of the galaxy must be less than  $M_B \leq -19$ . This criterion was applied for several reasons. Galaxies brighter than this can be taken to be ‘normal’ and applying the 2.2 magnitudes fainter criteria later ensures that the faint end of the LF, with all its uncertainties, is not reached for the neighbours. Again it also ensures, with the redshift data, that the catalogue is approximately complete. Other criteria applied are that the selected galaxies lie above a galactic latitude of  $|25^\circ|$  to minimise the effects of Galactic absorption and to ensure that only elliptical galaxies are selected we applied a  $t < -4$  type criterion to the LEDa database. Misclassification of galaxies is always a problem, particularly for elliptical galaxies where the presence of a disk or dust may lead to an erroneous morphological assignment, and it is possible that some S0’s may be included in this sample but the percentage should be very small. A visual inspection of the galaxies, together with a literature search, was undertaken to verify the morphological classification of the galaxies as ellipticals and also minimise the contamination. As the morphology of some of the galaxies was uncertain they have been retained in the catalogue and await a more detailed imaging study for an accurate classification. The heterogeneous nature of the construction of the LEDa catalogue almost certainly leads to an uncertain incompleteness limit. As the limiting apparent magnitude of our sample at the selected redshift cutoff is 16.8, it is highly likely that some galaxies will be missed due to a lack of redshift information. Although precluding a detailed statistical study of the population this does not, however, detract from our original desire to obtain a sample of elliptical galaxies in low density regions.

The total number of elliptical galaxies in the LEDa database that satisfy the selection criteria described above is 940. For each of these galaxies we have searched the LEDa database for galaxies that satisfy the ZSFw selection criteria. The first of these is that

any galaxy within 1 Mpc should be at least 8 times ( $=2.2$  mag) fainter than the primary. Secondly, the LEDA database was searched for any galaxy within a specified projected distance that was less than twice as faint as the primary candidate. Unlike previous studies, no redshift information was included in the selection process and thus these distances are projected. This is a much stricter criterion than many other studies, but ensures that any galaxies that satisfy the constraints are truly isolated. The 32 elliptical galaxies that we determine to be isolated are listed in Table 1, together with notes on the individual galaxies, taken from the NED database. A visual inspection of the Digitized Sky Survey scans was also undertaken to ensure that there were no bright galaxies in the field that had been missed in the LEDA catalogue.

#### 4. Changing the Parameters

How does the percentage of isolated galaxies vary as a function of magnitude limit of primary? or radial limits? To estimate the dependency of the field galaxy sample size with selection criteria we have applied an identical technique to that described above but have varied the inner radius cut-off from the fixed 500 kpc limit of ZSFW. The variation of the percentage of the morphological sample that are classified as ‘field’ with the inner radius cut-off is plotted in Fig. 2. Although closely related to the two-point correlation function, the addition of magnitude and redshift information in the production of this plot precludes a direct comparison. It is clear that there are elliptical galaxies that do not have companions within 2.2 magnitudes out to at least 1 Mpc.

To investigate the effect of incompleteness in the LEDA catalogue at fainter magnitudes, we have also used the same isolation and selection criteria except using an absolute magnitude of  $M_B < -20.5$ , corresponding to an apparent magnitude limit of  $B = 15.3$  at a redshift of  $10000 \text{ km s}^{-1}$ . The variation in the percentage of galaxies classified as isolated is shown in Fig. 2 as the dotted line. Although the number of ellipticals in this brighter sample is much smaller, 423 compared to 940, the percentage of galaxies that satisfy the isolation criteria is significantly higher at all radii than the fainter sample. There are several possible reasons for this. Firstly, by going to brighter magnitudes for the parent then, applying a magnitude limit to the companions, we sample only the brighter part of the galaxy number counts. Thus, a brighter sample will have many fewer companions than a fainter one, thus increasing the likelihood of the galaxy to be classified as isolated. Secondly, it is possible this is due to a selection effect in the catalogue construction. Finally, it may be an inherent luminosity segregation in the formation process of elliptical galaxies, similar to the creation of an anomalously bright galaxy in the core of some clusters, as seen in cD-dominated

or Bautz-Morgan Type I clusters. At present we cannot distinguish between these three possibilities. However, a similar investigation for spiral galaxies shows that by going to the brighter magnitude the percentage classified as field increases by a similar amount as for the elliptical sample. It is not, therefore, an effect that is due to an inherent property of the morphology of the galaxy.

## 5. The Environment of Field Ellipticals

Although the galaxies in Table 1 are isolated from other bright galaxies it is possible that they are surrounded by a halo of fainter, dwarf, galaxies. As a preliminary investigation of the environment of these galaxies we have used the technique first employed by Holmberg (1969) and extended by Phillipps and Shanks (1987) and Lorrimer et al. (1994). Due to their clustering properties, any excess in the number of galaxies seen in the field of the parent should be due primarily to objects of a similar redshift. This technique has been used extensively to determine the slope of the faint end of the LF in rich clusters (e.g. Driver et al. 1998) although inherent variations in the background may lead to an erroneous steepening of the slope (Valotto et al. 2001). However, this effect should not be important for individual galaxies although in this case the expected low numbers of companions will lead to large statistical errors. By stacking a number of galaxies, as used by ZSFW and Morgan et al. (1998), the statistical errors can be reduced and a ‘mean’ profile obtained.

Using the data publicly available from the APM plate-scanning machine we have detected all galaxies within a projected distance of 500 kpc of the parent. An absolute magnitude limit of  $M_{Bj} = -14.6$  for the surrounding galaxy population (assuming they are all at the redshift of the parent) and a redshift limit of  $6500 \text{ km s}^{-1}$  for the primary was applied to ensure that the APM scans were reasonably complete for high surface-brightness objects. It is well-known that at low surface-brightnesses the catalogue is incomplete. At magnitudes brighter than  $M_B = -16.8$  the criteria used to select the parent sample will lead to an incompleteness in the sample of dwarfs. A total of 10 galaxies in the sample of 32 had APM data suitable for this study. The resultant ‘mean’ radial density profile of the dwarfs surrounding the sample of 10 parents is shown in Fig. 3. It is clear that there is a significant excess of dwarf galaxies out to at least 500 kpc. To obtain an estimate of the dwarf population requires accurate subtraction of the contaminating background population. Incorrect subtraction can lead to widely varying values of the LF slope. With ZFSW finding very few satellites beyond 500 kpc we use the outer values of the radial profile as an estimate of the background. Fitting a power law to the resulting background-subtracted galaxy counts gives a power-law slope of  $-0.6 \pm 0.2$ . This is similar to the slope found for late-type galaxy

satellites by Lorrimer et al. (1994) but less steep than that found by them for early-type galaxies. However, they found a weak dependence of the slope on the satellite luminosity, with fainter galaxies having a flatter slope. Extrapolating their results to the magnitude limits reached in this study, there is good agreement with the value presented here. They did not find such a luminosity dependence of the slope for late-type galaxies.

There are, in total, an average of  $45 \pm 15$  dwarfs within 500 kpc of each primary down to the limiting magnitude of 14.6 and  $19 \pm 6$  with  $-16 < M_B < -15$ . Brighter than  $-16$  the number of satellites agrees with the values of Lorrimer et al (1994). Comparing the number of faint dwarfs to the values for brighter satellites implies a steep luminosity function ( $\alpha \sim -1.8$ ), in approximate agreement with that found for poor clusters (e.g. Driver et al. 1998) and also the value derived by Morgan et al. (1998) for isolated spirals. This lends some support to the CDM model of hierarchical structure formation (e.g. White and Frenk 1991), where there should be an abundance of small dark matter halos. However, the field luminosity function has a slope of  $-1.2$  (e.g. Norberg et al. 2002, Davies et al. 2003) suggesting the dominance of dwarf galaxies varies considerably between environments. The errors in Fig. 3 are much larger than Poissonian, suggesting that there are intrinsic variations in the dwarf population surrounding the parent ellipticals. However, the sample size of dwarfs around individual ellipticals is too small for any significant conclusions to be drawn. If the slope of the LF is steep around field ellipticals, a deeper and higher resolution imaging study should enable the unambiguous detection of this dwarf population and possibly investigate the galaxy-to-galaxy variation of the dwarf density. A dynamical study, as undertaken by ZSFW, is also required to determine which of the brighter neighbours are truly satellites of the central elliptical and hence obtain an estimate of the size (and mass) of its halo.

## 6. Conclusions

We have identified a sample of elliptical galaxies that lie in regions where the local density of bright ( $M_B < -17$ ) galaxies is very low, indicating that such objects are not exclusively associated with groups or clusters of galaxies. A study of the local environment around them shows an excess of faint galaxies, presumably satellites, out to a projected distance of at least 500 kpc and with a projected density varying as  $r^{-0.6 \pm 0.2}$ . The numbers of these dwarfs suggests a steep faint end of the luminosity function, in contradiction to that found for the field but in good agreement with that found for the outer regions of clusters. A considerable number of questions remain which can only be answered through a more detailed study of these objects and their environment.

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We have made use of the LEDA database (<http://leda.univ-lyon1.fr>)

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Table 1: Isolated ellipticals

PGC	Other Name	RA(2000)	Dec(2000)	Vel (km s <sup>-1</sup> )	B	Notes
8160	NGC 821	02 08 21.1	+10 59 42	1735	11.90	Possible stellar disk
37366	NGC 3962	11 54 40.1	−13 58 30	1815	11.75	Gaseous disk
63620	IC 4889	19 45 15.8	−54 20 37	2574	12.02	Dust disk - possible S0
71730	IC 5328	23 33 17.0	−45 01 01	3137	12.29	Group member
60536	NGC 6411	17 35 32.4	+60 48 48	3806	13.02	
27600	NGC 2954	09 40 24.1	+14 55 22	3821	13.60	
72867	NGC 7785	23 55 19.0	+05 54 57	3808	12.62	Extended envelope
11274	NGC 1162	02 58 56.0	−12 23 55	3939	13.49	
15406	NGC 1600	04 31 39.8	−05 05 10	4688	12.04	Group member
62342	NGC 6653	18 44 38.4	−73 15 48	5163	13.35	Possible SA(rs)0
1037	NGC 57	00 15 30.9	+17 19 42	5440	12.87	
7252	NGC 741	01 56 21.0	+05 37 44	5561	12.30	Group member
28220	NGC 3017	09 49 03.0	−02 49 19	6229	14.45	
9858	IC 1819	02 35 41.8	+04 03 06	6393	15.29	Probable S0
45976	NGC 5028	13 13 45.8	−13 02 33	6433	13.72	
70262	KUG 2258+193	23 01 07.1	+19 36 33	6473	15.21	Sc
3090	NGC 282	00 52 42.1	+30 38 21	6673	14.43	
61167	NGC 6515	17 57 25.2	+50 43 41	6853	13.96	
4808	AM0118-500	01 20 13.4	−49 49 47	7500	14.87	
57841	CGCG 052-004	16 19 48.1	+05 09 44	7494	14.76	
473	MRK 335	00 06 19.5	+20 12 10	7730	13.64	Seyfert 1, S0?
16415	ESO 033-G003	04 57 47.6	−73 13 54	7664	14.25	Possible SA0, behind LMC
55698	ARK 481	15 39 05.1	+05 34 16	7781	15.24	
170383		22 01 23.5	−03 45 24	8001	15.13	Not in NED
7468	NGC 766	01 58 42.0	+08 20 48	8104	14.24	Group member
170381		22 01 05.0	−04 47 51	8248	15.46	Not in NED
65215	MCG-02-52-019	20 41 48.4	−13 50 49	8409	14.74	
7862	MCG-05-06-002	02 03 56.3	−31 47 09	8363	14.74	
60164	NGC 6363	17 22 40.0	+41 06 06	8912	15.17	
57371	CGCG 320-009	16 10 21.0	+67 50 11	8914	15.37	Early spiral?
25560	CGCG 005-056	09 06 39.5	−00 51 55	9058	15.37	NED S0
54129	CGCG 165-027	15 10 08.8	+31 53 16	9206	15.32	NED S?

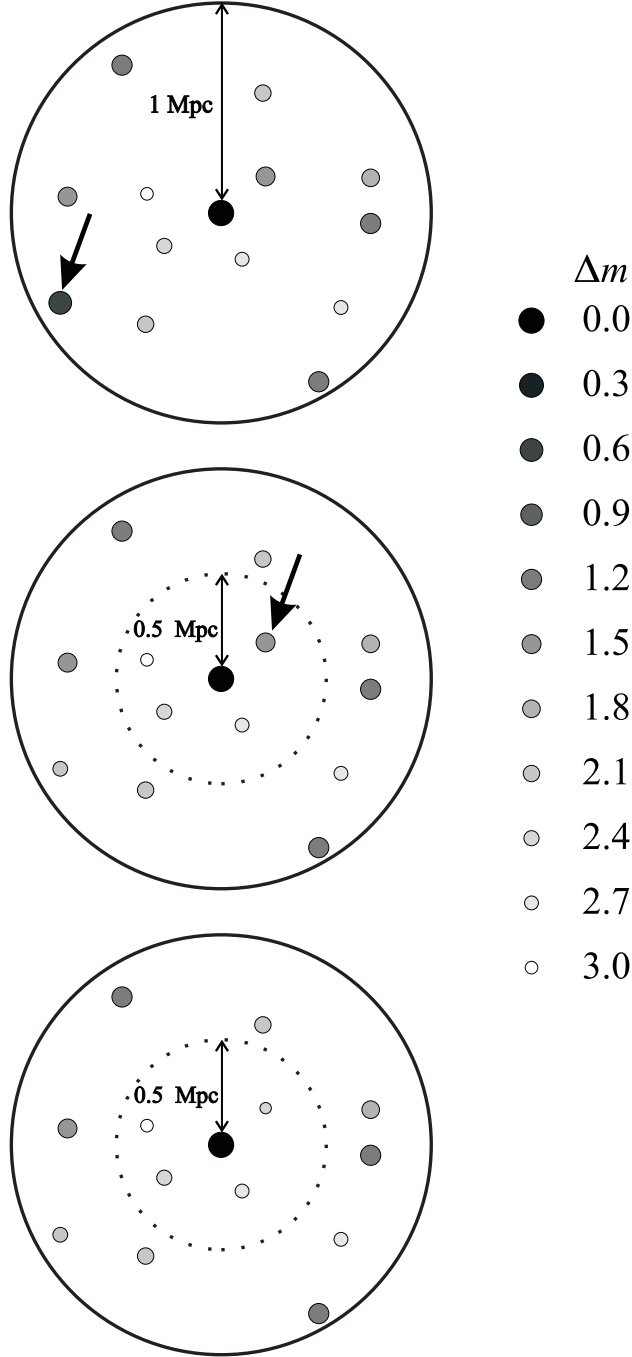


Fig. 1.— The isolation criterion is illustrated in this plot. The top panel shows the situation when the central galaxy does not verify the first condition of the criterion because it has a bright companion (indicated by the arrow), with a magnitude difference less than 0.7 within 1 Mpc of projected separation. In the middle panel, the galaxy verifies this condition, but fails to be considered isolated because the second condition is not accomplished: it has a companion with a magnitude difference less than 2.2 within 0.5 Mpc of projected distance, (again it has been marked with an arrow). Finally, the bottom panel shows the case where the central galaxy verifies the two conditions of the isolation criterion.

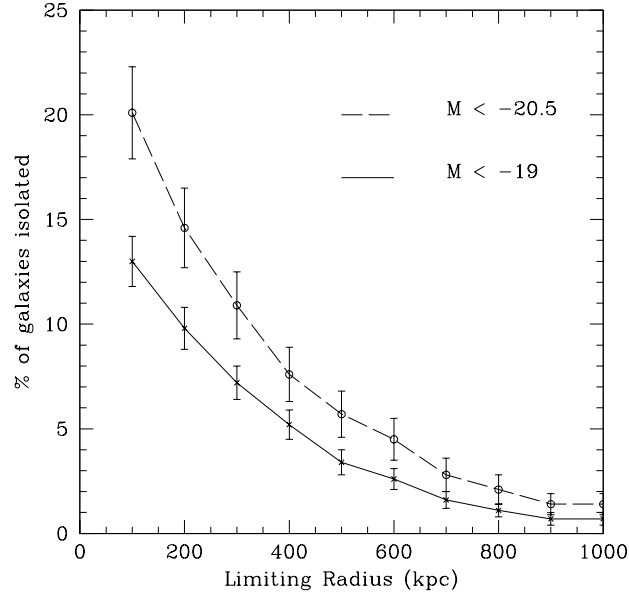


Fig. 2.— Variation of the percentage of elliptical galaxies classified as isolated as a function of the inner cut-off radius for galaxies within 2.2 magnitudes of the primary. Two values for the limiting absolute magnitude of the primary are shown.

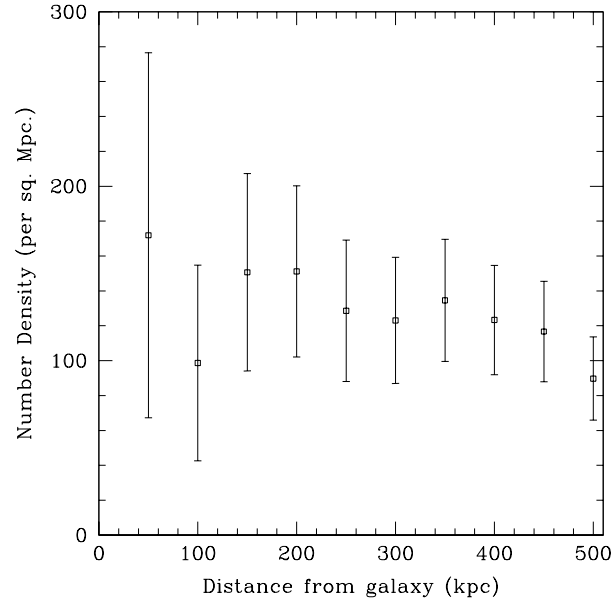


Fig. 3.— Mean radial galaxy density profile for dwarf galaxies surrounding 10 of the 32 galaxies taken to be ‘isolated’.